

# A Simple Phase-Shifting Cell for Reflectarray Using a Slot Loaded with a Ferroelectric Capacitor

Kevin Nadaud<sup>1</sup>, Raphaël Gillard<sup>2</sup>, Erwan Fourn<sup>2</sup>, Hartmut W. Gundel<sup>1</sup> and Caroline Borderon<sup>1</sup>

<sup>1</sup>IETR, UMR 6164/University of Nantes, Nantes, France

<sup>2</sup>IETR, UMR 6164/INSA of Rennes, Rennes, France

Email: kevin.nadaud@univ-nantes.fr, raphael.gillard@insa-rennes.fr

**Abstract**—A tunable reflectarray phase-shifting cell, designed for a resonance frequency of 5.6 GHz, is presented. The cell is based on a simple slot topology and loaded by a ferroelectric thin film capacitor of 60% tunability under 400 kV/cm bias electric field. The cell provides 245 degrees of phase-shifting.

**Index Terms**—Ferroelectric, reflectarray, thin film, tunability.

## I. INTRODUCTION

Today, planar reflectarrays are widely studied because they combine the advantages of printed array antennas and reflector antennas [1]. A planar reflectarray basically consists of a flat panel made with a large number of reflecting unit-cells illuminated by a primary source (typically a horn antenna). By properly adjusting the reflected phase of each cell, any radiated beam can be formed. Neither a lossy feeding network nor a costly shaped reflector is needed, which paves the way to large radiating apertures with both, high efficiency and reduced complexity.

Reconfigurable reflectarrays are even more attractive as they allow steering or shaping the radiated beam by using tunable components in order to change the reflected phase of the individual unit-cells. Different active cells have been reported in the literature. Most of them use electronic devices such as varactors [2] or PIN diodes [3]. Others rely on the integration of MEMS switches in the radiating cells [4]. Advanced tunable materials like Liquid Crystals [5] or ferroelectrics [6], [7] can also be used. The main advantage of ferroelectric materials is the absence of bias current, which considerably reduces power consumption. The topology studied in [6], [7] is a patch divided into two parts with a ferroelectric film in the separating gap. Simulations, however, do not include the biasing circuit, which result in high losses when it is added in practice.

Another quite simple topology has been proposed in [8] where a single tunable capacitor is used in order to load a slot in the ground plane. Although the concept seems to be promising, no demonstration has been done yet involving actual active elements. In this paper, we propose an experimental validation where a ferroelectric thin film has been used in order to establish the variable capacitance and where the polarization circuit has been optimized by simulation. For the proof of concept, a simplified unit-cell which requires only one single slot has been used.

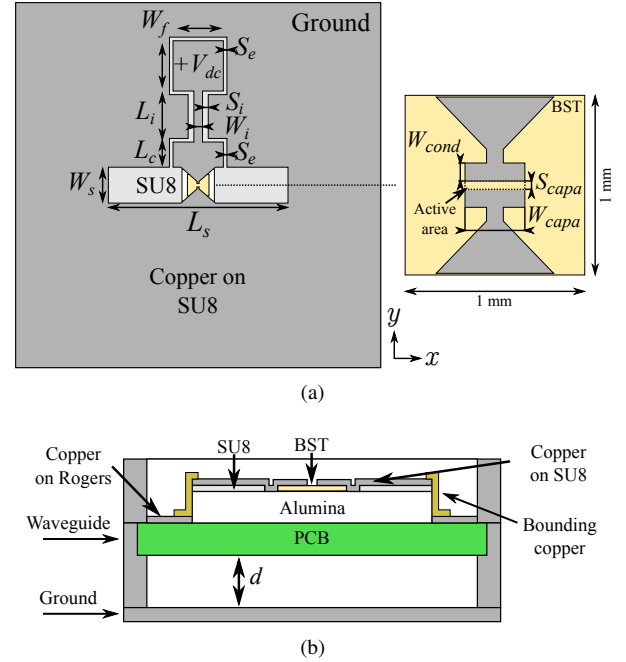


Figure 1. Topology of the proposed cell and zoom on the capacitor region (a). The dielectric stack in the waveguide (b).  $L_s = 12.5$  mm ;  $W_s = 2.5$  mm ;  $W_f = 4$  mm ;  $W_i = 600$   $\mu$ m ;  $S_i = 400$   $\mu$ m ;  $L_i = 2.7$  mm ;  $L_c = 2$  mm ;  $S_e = W_{cond} = 30$   $\mu$ m ;  $W_{capa} = 100$   $\mu$ m ;  $S_{capa} = 7$   $\mu$ m ;  $d = 15.7$  mm.

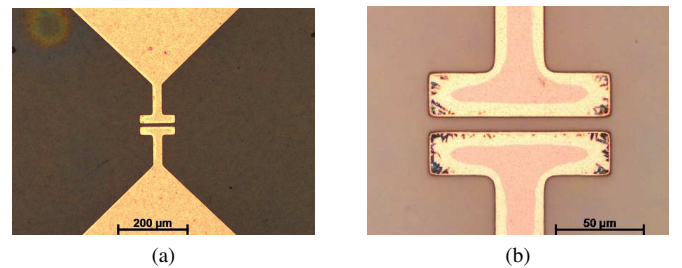


Figure 2. Optical photograph of the tunable ferroelectric capacity (a) and zoom on the capacitor gap (b).

## II. THE FERROELECTRIC MATERIAL

Ferroelectrics are non-linear materials well known for their high and tunable relative permittivity. They can be used in different microwave devices such as phase-shifters, filters, antennas or reflectarray cells. Several materials are avail-

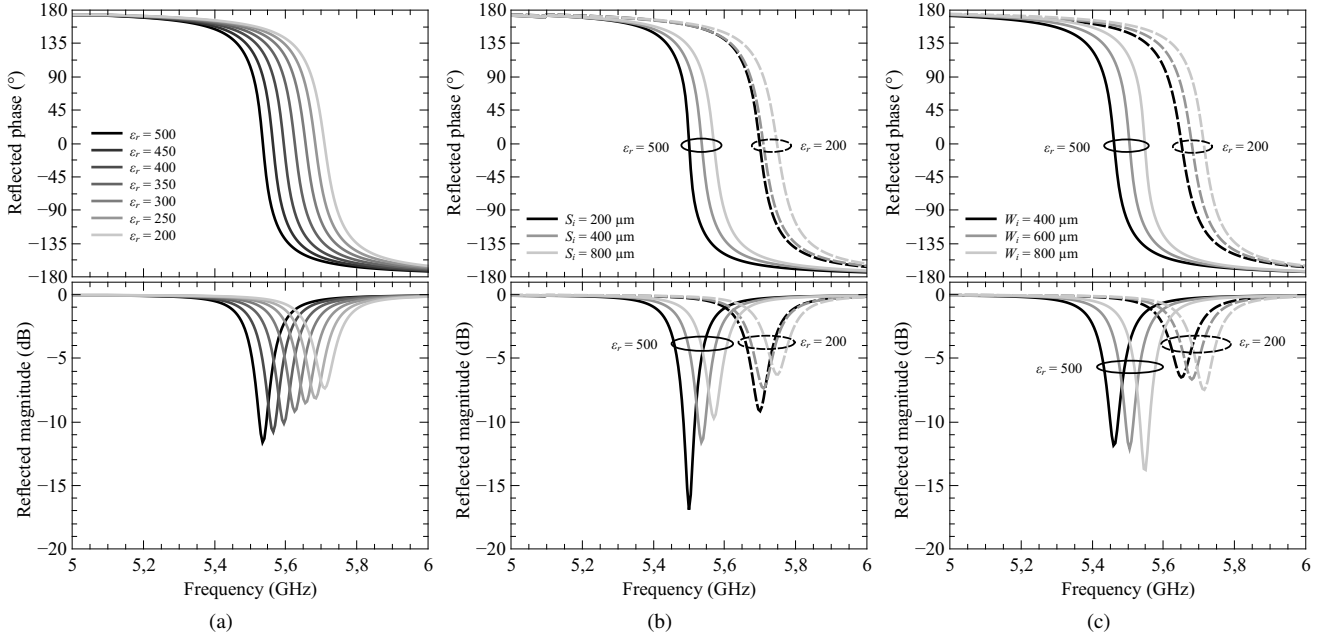


Figure 3. Simulated reflection coefficient (phase and magnitude) of the proposed cell for different relative permittivity values of the ferroelectric thin film (a). Influence of the gap width  $S_i$  (b) and of the line width  $W_i$  (c) of the biasing circuit on the reflection coefficient.

able: Barium-Strontium-Titanate (BST), Potassium-Niobium-Titanate (KTN) or Lead-Zirconium-Titanate (PZT).

In the proposed device, BST has been chosen because of its relatively low dielectric losses and a high tunability. Moreover BST has a low coercive field, which considerably reduces the hysteresis effect and thus simplifies the electric command.

The films were elaborated on alumina substrates by chemical solution deposition (CSD) [9]. A one-percent manganese-doping has been used in order to reduce low frequency leakage currents and to prevent from breakdown while biasing the material. Dielectric characterization has been performed using a technique described in [10]. At 5 GHz, the thin films have a relative permittivity of 500, a tunability of 60% under 400 kV/cm and a  $\tan \delta = 0.02$ . Details of the material characterization shall be published elsewhere.

### III. THE CELL DESIGN

The proposed unit-cell consists of a simple slot in a ground plane as shown in Fig. 1a and is designed for operation at 5.6 GHz. The electrical length of the slot controls the resonant frequency and thus the resulting phase-shift when an incident wave impinges on the cell. By loading the slot with a tunable capacitor, it is possible to change its electrical length dynamically.

For the sake of simplicity (regarding measurement), the cell is embedded in a  $35 \times 35$  mm<sup>2</sup> square metallic waveguide. Fig. 1b shows the details of the used dielectric stack. The alumina substrate ( $25.4 \times 25.4$  mm<sup>2</sup>, thickness 508  $\mu$ m and relative permittivity 9.8) with the BST thin film is reported on a printed circuit board (PCB, permittivity 2.17, losses  $9.10^{-4}$  and thickness 1.6 mm) which is mounted 15.7 mm above the

ground plane ending the metallic waveguide. In order to reduce dielectric losses, the ferroelectric material has been limited by wet etching to only a  $1 \times 1$  mm<sup>2</sup> surface which is sufficient for hosting the capacitor. The thickness of the ferroelectric film is 1  $\mu$ m. The electrode metallization (1.4  $\mu$ m thick) is realized by sputtering copper and patterning with a classical photolithography process. In order to flatten the substrate's surface before metallization, the alumina substrate has been coated with a 1.2  $\mu$ m thick SU8 epoxy. The length  $L_s$  and the width  $W_s$  of the slot have been optimized in order to maximize the achievable phase range at 5.6 GHz while minimizing the cell losses.

The ferroelectric capacitor consists of two coplanar plates deposited on the ferroelectric film (Fig. 2). This topology was preferred to a more standard MIM (Metal Insulator Metal) topology in order to reduce the number of fabrication steps and also to avoid possible misalignment issues. The distance between the electrode plates  $S_{capa}$  is 7  $\mu$ m. The biasing circuit can be seen in Fig. 1a. Isolation of the biased electrode from the ground is done by a narrow gap ( $S_e$  width). A low-pass distributed filter is also necessary for improving the decoupling between the DC bias and the RF signal. It consists of an inductive line (width  $W_i$  and length  $L_i$ ) followed by a capacitive line (width  $W_f$  and length  $L_c$ ).

### IV. SIMULATIONS

Simulations of the unit-cell have been performed with HFSS<sup>TM</sup> commercial software. As stated above, the cell is simulated in a  $35 \times 35$  mm<sup>2</sup> metallic waveguide. The excited mode is the TE<sub>10</sub> mode (according to the axis of Fig. 1a). In order to obtain only one propagating mode polarized along the

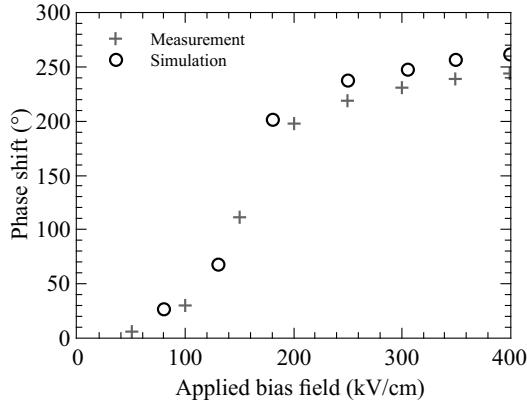


Figure 4. Simulated and measured phase shift of the proposed cell as a function of the applied bias field on the material.

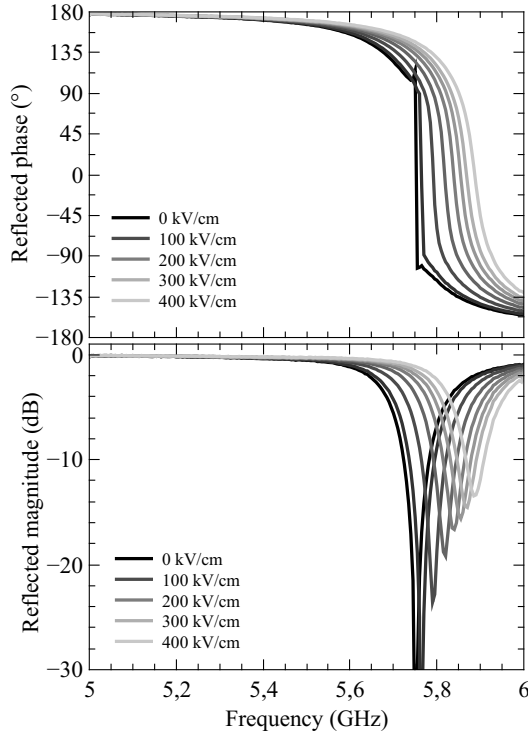


Figure 5. Measured reflection coefficient of the proposed cell.

$y$  axis, the simulation has been carried out from 5 to 6 GHz. The cross polarization has not been considered since the cell is symmetrical.

Note that one simulation is needed for each value of the ferroelectric relative dielectric permittivity. Simulation has been performed in steps of 50 from 500 to 200, corresponding to the permittivity of the ferroelectric thin film without bias and under 400 kV/cm bias electric field, respectively. For the simulations, the ferroelectric material is divided into two areas. A central area corresponding to a parallelepiped whose horizontal section is delimited by the two electrodes of the capacitor (see Fig. 1). This is the active part of the material which is directly exposed to the bias field. As a consequence,

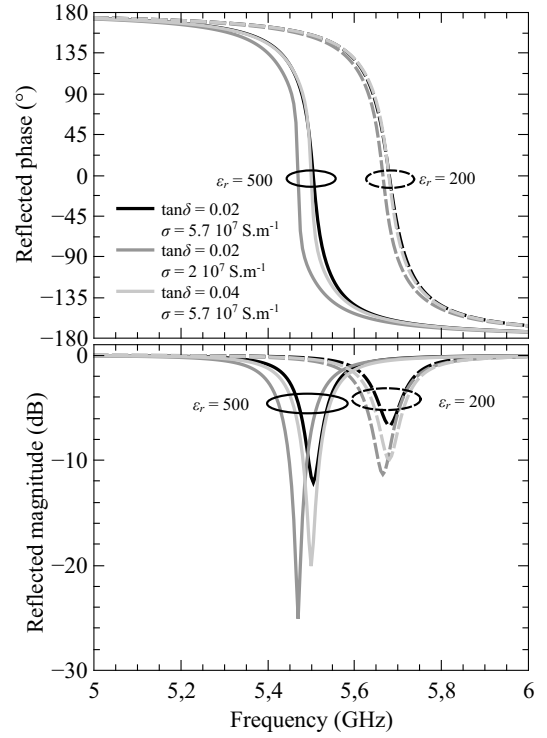


Figure 6. Retro-simulation of the cell with different values for the material's dielectric losses and the conductivity of the metallization.

the dielectric constant in this central area is supposed to be bias-dependent and thus has been varied from one simulation to the other. On the other hand, the remaining part of the ferroelectric material (periphery area around the electrodes) is supposed to be independent from the applied bias as the concentration of the static field is much lower. Hence, for all simulations the same zero-bias permittivity has been used in this area.

The simulation results of the reflected phase and amplitude are shown in Fig. 3. With a supposed tunability of the ferroelectric material of 60%, the phase range achieved by the cell at the central frequency 5.6 GHz is 260° (Fig. 3a). The influence of the gap width  $S_i$  and of the line width  $W_i$  of the low pass filter is presented in Fig. 3b and 3c respectively. A large gap or a small line help to reduce losses but the phase-shift obtained for a fixed tunability is also lower. A gap width of 400  $\mu\text{m}$  and a line width of 600  $\mu\text{m}$  seem to be a compromise, allowing to obtain sufficient phase-shift while limiting the losses to 12 dB.

## V. MEASUREMENT

In order to perform the measurements, the cells are located in a square metallic waveguide fed with a standard WR137 rectangular waveguide through a rectangular-to-square transition [8]. The reference plane is set on top of the alumina substrate and three offset shorts are used for calibration [11].

The phase shift of the cell central frequency as a function of the DC bias electric field applied to the ferroelectric capacity is shown in Fig. 4. The values obtained from the measurements

are in good agreement with those found in the simulations. An overall phase shift of  $245^\circ$  can be seen for the permittivity tunability of 60% under 400 kV/cm.

For the moment, characterization of the cells shows higher losses (Fig. 5) as compared to the simulation. Measurement of the conductivity of the deposited metallization, however, gives  $2 \cdot 10^7 \text{ S.m}^{-1}$  which is considerably lower than the bulk value for copper. Retro-simulations on the cell sensitivity hence have been performed in order to determine the origin of the losses. They may possibly come from an underestimation of the material's dielectric losses or a smaller conductivity of the deposited metal. Fig. 6 shows the influence of the dielectric losses of the ferroelectric material and of the conductivity of the metallization on the reflection coefficient. As can be seen, the cell is especially sensitive to the metallization conductivity. Work is in progress in order to improve the quality of the copper deposition such as to obtain better performances.

From Fig. 5 one can also see that the measured resonant frequency at zero bias field is approximately 200 MHz higher than in simulation. This may be due to geometric imperfections stemming from the precision limit of the realization process or caused by small variation of the dielectric characteristics of the ferroelectric material. Another explanation could be the possible presence of a thin air-gap between the two substrates, which would affect the electrical length of the slot.

## VI. CONCLUSIONS

A tunable reflectarray cell using a ferroelectric capacitor has been realized. It has been designed for a frequency of 5.6 GHz and has been measured with a WR137 waveguide. The evolution of the phase-shift as function of the applied bias field is in good agreement between simulation and measurement. Simulations shows that a phase-shift of  $260^\circ$  can be achieved with a tunability of the material's permittivity of 60%. In measurement, the phase-shift achieved is  $245^\circ$ . In the case of the used BST thin film, this corresponds to an applied bias electric field of 400 kV/cm (equal to 280 V across the  $7 \mu\text{m}$  capacitor gap  $S_{\text{capa}}$ ). Moreover, the simulations take into account the biasing circuit which is a critical element in active unit-cells and has been optimized in order to reduce the losses

while maintaining a sufficient phase-shift.

In simulation, the losses reach up to 12 dB, which is close to the state of the art, the obtained phase-shift, however, is considerably higher than reported before ( $260^\circ$  instead of  $80^\circ$ ) [6]. The proposed reflectarray cell may be improved by reducing the capacitor gap width (which is a technological issue only). This would allow either a higher tunability and hence phase-shift for a given bias electric field or reduction of the necessary driving voltage when maintaining the cell agility constant.

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